PATENT APPLICATION
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LD PUMPED FIBRE AMPLIFIER WITH SECOND RESONATOR OR INPUT

SIGNAL FOR GAIN LIMITATION

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LD PUMPED FIBRE AMPLIFIER WITH SECOND RESONATOR OR INPUT SIGNAL FOR GAIN LIMITATION

Cross Reference to Related Applications

The present application is a U.S. National Stage filing of Patent Cooperation Treaty ("PCT") application serial number PCT/GB2004/003330, filed 02 August 2004, which in turn claims priority to United Kingdom (Great Britain) Patent Application Serial Number GB 0317952.0, filed 31 July 2003, both of which are hereby incorporated by reference herein in their entirety.

Field of Invention

This invention relates to an apparatus for providing optical radiation. The invention has particular relevance for high-power fibre lasers, and for welding, drilling, cutting and marking applications.

Background to the Invention

Fibre lasers are increasingly being used for material processing applications such as welding, cutting and marking. Their advantages include high efficiency, robustness and high beam quality.

Traditional lasers used for material processing applications predominate at around 1.06μm and longer wavelengths such as provided by a carbon dioxide laser (10.6μm). These lasers are being supplemented by fibre lasers operating at around 1.06μm.

High power fibre lasers and amplifiers are also finding application in coherent combining systems, in which the output from parallel lasers or amplifiers are coherently combined together. These systems are either based on parallel master oscillator power amplifiers driven from a common source such as a distributed feedback laser, or use parallel lasers and rely on feedback to phase lock the lasers together.

High power fibre lasers are often single mode and are often pumped at high intensity levels. If insufficient optical power is provided to saturate the gain medium, very high inversion levels can result in giant pulse generation, often referred to as "self Q-switching". The result can be catastrophic failure of the optical fibre gain

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1 medium, pump diodes and other optical components within the laser because the

2 generated giant pulse is of such high intensity or contains so much optical energy

3 that it can destroy the components. Voids can appear along the cores of optical

4 fibres, laser diodes can be damaged such that they no longer emit optical radiation,

5 and optical surfaces can be damaged. Such failures can be a particular problem

6 with high-power Q-switched lasers, because these contain an amplifier that is

7 designed to store energy when the Q-switch is open, and to release the energy in

8 the form of a pulse when the Q-switch is closed. If the Q-switch is not closed often

9 enough, or if a laser cavity is not formed when the Q-switch is closed through

10 misalignment or other failure, then large amounts of stored energy can be built up

11 within the amplifier which can be released through a self Q-switching or other

12 . mechanism resulting in a giant pulse of sufficient energy to damage the amplifier.

13 Failures can also be a problem with master oscillator power amplifiers. If the power

14 amplifier is operated without an input signal, then the amplifier will store optical

15 energy which can be released in a giant pulse that destroys optical components

16 within the power amplifier. The failure can also be a problem for material processing

17 systems that require very high reliability for 24 hour 7 days per week operation.

18 Even though self Q-switching events may be very rare, it would be altogether better

19 to ensure that the amplifiers are unable to release stored energy in a manner that

20 would destroy the product.

21 An aim of the present invention is to provide apparatus for providing optical

22 radiation that reduces the above aforementioned problem.

23

24 **Summary of the Invention**

25 According to a non-limiting embodiment of the present invention, there is

26 provided apparatus for providing optical radiation having a signal wavelength, which

27 apparatus comprises at least one pump for providing pump radiation, a gain medium,

28 and energy limiting means, in which the pump radiation acts on the gain medium to

29 provide stored energy and gain for optical amplification, characterised in that the

30 gain has a maximum gain at a wavelength at which the maximum gain occurs, and

31 the energy limiting means limits the maximum gain and the amount of stored energy

32 that is able to be stored to values below those at which the stored energy will cause

33 damage to the apparatus.

1   The stored energy and gain in apparatus for providing optical radiation having
2   a signal wavelength, for example an optical amplifier or a laser, arise from the
3   inversion of the gain medium when pumped by the pump. In the absence of an input
4   signal, the gain medium can become heavily inverted leading to large amounts of
5   stored energy and optical gain. Without use of the energy limiting means, the
6   available gain at small intensities of the input signal can be so large that a very small
7   perturbation at the input could extract a significant amount of stored energy in a
8   single or few passes to a level that can damage the apparatus. For example, in a
9   ytterbium-doped fibre amplifier, a 1ns input pulse arising out of noise that is allowed
10   to extract 1mJ of stored energy will provide an output pulse having 1MW of optical
11   power, more than is sufficient to damage the optical fibre for example by creating
12   voids in its core. The energy limiting means of the present invention ensures that the
13   stored energy and gain are such that the stored energy is unable to be released in a
14   way that would damage the apparatus.

15   The gain medium may be such that the signal wavelength and the wavelength
16   at which the maximum gain occurs are separated by less than 10nm. This is
17   preferred to make optimal use of the maximum gain in that the energy limiting means
18   has to do less work in order to ensure that the stored energy is unable to damage
19   the apparatus. Alternatively, the gain medium may be such that the signal
20   wavelength and the wavelength at which the maximum gain occurs are separated by
21   at least 10nm. In this case, it is preferred that the energy limiting means operates
22   around the maximum gain.

23   According to a first embodiment of the present invention, the energy limiting
24   means comprises first and second reflectors characterised by first and second
25   reflectivities and an energy limiting wavelength, the first and second reflectors
26   forming a cavity about the gain medium, and the first and second reflectors being
27   such that they limit the available gain when the gain medium is pumped by the pump
28   such that the stored energy is unable to cause damage to the apparatus.

29   The first reflectivity may be greater, the same as, or less than the second
30   reflectivity. At least one of the first and second reflectors may be designed to reflect
31   at least 0.01% of optical radiation at the energy limiting wavelength.

32   The product of the first and second reflectivities may be substantially equal to
33   the reciprocal of twice the small signal gain at the energy limiting wavelength.

1   The apparatus may be such that the gain medium is pumped by at least 1W

2   of the pump radiation, and the maximum gain may be less than 40dB.

3   The gain medium may be pumped by at least 10W of the pump radiation, and

4   the maximum gain may be less than 30dB.

5   The gain medium may be pumped by at least 100W of the pump radiation,

6   and the maximum gain may be less than 25dB.

7   The gain medium may be pumped by at least 1000W of the pump radiation,

8   and the maximum gain may be less than 20dB.

9   According to a second embodiment of the present invention, the gain medium

10   is pumped by the pump radiation at a pump power of at least 1W, and in which the

11   energy limiting means comprises an optical source that provides at an energy

12   limiting wavelength an energy limiting power greater than -40dB relative to the pump

13   power, which energy limiting power acts on the gain medium to reduce the amount of

14   stored energy and gain when the gain medium is pumped by the pump such that the

15   stored energy is unable to cause damage to the apparatus.

16   The gain medium may be pumped by at least 10W of the pump power, and

17   the energy limiting source may provide an energy limiting power greater than -30dB

18   relative to the pump power.

19   The gain medium may be pumped by at least 100W of the pump power, and

20   the energy limiting source may provide an energy limiting power greater than -25dB

21   relative to the pump power.

22   The gain medium may be pumped by at least 1000W of the pump power, and

23   the energy limiting source may provide an energy limiting power greater than -20dB

24   relative to the pump power.

25   In the first and second embodiments, the energy limiting wavelength may be

26   in the same emission band as the signal wavelength. Alternatively the energy

27   limiting wavelength may be in a different emission band from the signal wavelength.

28   The energy limiting wavelength may be greater than the signal wavelength.

29   Alternatively, the energy limiting wavelength may be less than the signal wavelength.

30   The energy limiting wavelength and the wavelength at which the maximum

31   gain occurs may be separated by less than 10nm. This is preferable in order to

32   reduce the amount of energy limiting signal. Alternatively, the energy limiting

33   wavelength and the wavelength at which the maximum gain occurs may be

1   separated by at least 10nm which facilitates filter the energy limiting signal from the
2   output radiation.
3   In all embodiments of the invention, the apparatus may include a scanner into
4   which the optical radiation is coupled. The apparatus may include a controller for
5   synchronizing the optical radiation with the scanner. Such apparatus is useful for
6   material processing applications such as welding, cutting, brazing and drilling.
7   In all embodiments of the invention, the gain medium may form part of an
8   optical fibre. The optical fibre may comprise rare-earth dopant.
9   The optical fibre may be a cladding pumped optical fibre comprising a core,
10 an inner cladding for guiding pump radiation supplied by the pump, and an outer
11 cladding, and in which the rare earth dopant is disposed in at least one of the core
12 and the inner cladding.
13   The rare-earth dopant may be selected from the group comprising Ytterbium,
14 Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and
15 Dysprosium, Erbium codoped with Ytterbium, or Neodymium codoped with
16 Ytterbium.
17   The apparatus may be in the form of an amplifier, a laser, a master oscillator
18 power amplifier, a Q-switched laser, a source of amplified spontaneous emission, or
19 a continuous wave laser.
20   The apparatus may be in the form of a laser for material processing.
21
22   **Brief Description of the Drawings**
23   Embodiments of the invention will now be described solely by way of example
24 and with reference to the accompanying drawings in which:
25   Figure 1 shows apparatus for providing optical radiation according to the
26 present invention;
27   Figure 2 shows apparatus in the form of a Q-switched laser;
28   Figure 3 shows the variation of inversion with time in a Q-switched laser;
29   Figure 4 shows the optical output of a Q-switched laser;
30   Figure 5 shows the output of the energy limiting means with time;
31   Figure 6 shows variation of inversion with time in a Q-switched laser that has
32 been gain clamped;

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1   Figures 7 shows the optical output of a Q-switched laser that has been gain

2   clamped;

3   Figure 8 shows the output of the energy limiting means with time from a Q-

4   switched laser that has been gain clamped;

5   Figure 9 shows apparatus in the form of a Q-switched laser in which the

6   energy limiting means comprises an optical source;

7   Figure 10 shows apparatus in the form of a master oscillator power amplifier;

8   Figure 11 shows apparatus in the form of an optical amplifier that comprises a

9   cavity;

10   Figure 12 shows apparatus in the form of an optical amplifier that comprises

11   an optical source;

12   Figure 13 shows apparatus in the form of a master oscillator power amplifier;

13   Figure 14 shows apparatus in the form of a material processing system

14   comprising a plurality of seed lasers

15   Figure 15 shows an amplifier that is gain clamped with two fibre Bragg

16   gratings;

17   Figure 16 shows the gain as a function of pump power measured in the

18   amplifier of Figure 15;

19   Figure 17 shows optical spectra measured at the output of the amplifier of

20   Figure 15;

21   Figure 18 shows the gain of the amplifier measured with different fibre Bragg

22   gratings;

23   Figure 19 shows the gain spectra measured as a function of wavelength;

24   Figure 20 shows gain and grating reflectivity design curves;

25   Figures 21, 23, and 25 show gains for amplifiers with and without energy

26   limiting power for various levels of pump power; and

27   Figures 22, 24, and 26 show small signal gains as a function of wavelength

28   corresponding to the amplifiers of Figures 21, 23 and 25.

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Detailed Description of Preferred Embodiments of the Invention

2   With reference to Figure 1, there is provided apparatus 10 for providing optical

3 radiation 3 having a signal wavelength λ_s 4, which apparatus 10 comprises at least

4 one pump 5 for providing pump radiation 15, a gain medium 6, and energy limiting

5 means 2, in which the pump radiation 15 acts on the gain medium 6 to provide

6 stored energy 7 and gain 8 for optical amplification, characterised in that the gain 8

7 has a maximum gain 14 at a wavelength 18 at which the maximum gain 14 occurs,

8 and the energy limiting means 2 limits the maximum gain 14 and the amount of

9 stored energy 7 that is able to be stored to values below those at which the stored

10 energy 7 will cause damage to the apparatus 10. Figure 1 shows the gain medium 6

11 and the pump 5 being part of a first amplifier 1. The gain 8 is shown over an

12 emission band 9 as a function of wavelength 12. The signal wavelength λ_s 4 is

13 preferably within the emission band 9. The energy limiting means 2 can be a part of

14 the first amplifier 1 or be provided externally to the first amplifier 1.

15   Figure 2 shows apparatus in the form of a Q-switched laser 20 which contains

16 the first amplifier 1 and the energy limiting means 2. The first amplifier 1 is an optical

17 fibre amplifier comprising a pump 5 and a pump coupler 22. The gain medium 6 is

18 provided by a rare-earth doped fibre 23. The pump 5 can be a fibre laser, a

19 semiconductor laser diode, a laser diode bar, a laser diode stack, or a module

20 comprising a plurality of semiconductor laser diodes, bars or stacks. The rare-earth

21 doped fibre 23 can comprise an optical fibre doped with ytterbium, erbium, thulium,

22 neodymium or holmium, or co-doped with one or more of these rare-earth ions, such

23 optical fibre being operated as a two, three or four level laser system. The pump

24 coupler 22 can be an optical coupler. Alternatively, the pump coupler 22 can

25 comprise one of the many optical arrangements used to core pump or cladding

26 pump rare-earth doped fibres such as the rare-earth doped fibre 23. Such optical

27 arrangements include using V-grooves etched or machined into the fibre 23, side

28 pumping via another optical fibre, or using dichroic mirrors. The Q-switched laser 20

29 also comprises an optical switch 24, and third and fourth reflectors 25, 26. The

30 optical switch 24 is shown as an acousto-optic modulator in Figure 2, but can be a

31 Q-switch comprising a Pockels cell, a Kerr cell. Alternatively, the optical switch 24

32 can be an electo-optic switch such as one made from lithium niobate. The third and

1 fourth reflectors 25, 26 can be gratings, fibre Bragg gratings, dichroic mirrors, or
2 other reflectors commonly used in waveguide lasers.

3   The energy limiting means 2 comprises a first cavity 27. The first cavity 27 is
4 formed by first and second reflectors 281, 282 characterised by first and second
5 reflectivities 283, 284 and an energy limiting wavelength λ_l 285. The first and second
6 reflectors 281, 282 are such that they limit the maximum gain 14 when the rare-earth
7 doped fibre 23 is pumped by the pump 5. This is achieved by configuring the first
8 cavity 27 to lase by appropriate selection of the first and second reflectors 281, 282
9 in order to generate an energy limiting signal 29 at the energy limiting
10 wavelength λ_l 285. The energy limiting wavelength 285 is preferably a different
11 wavelength than the signal wavelength λ_s 4. The first cavity 27 will in general emit
12 part of the energy limiting signal 29 through the first and second reflectors 281, 282.
13 The first and second reflectors 281, 282 can be gratings, fibre Bragg gratings,
14 dichroic mirrors, or other reflectors commonly used in waveguide lasers. The
15 functions of the second reflector 282 and the fourth reflector 26 can be combined in
16 a single reflector that reflects at both the signal wavelength λ_s 4 and the energy
17 limiting wavelength λ_l 285

18   Figure 3 shows the inversion 33 N of the rare-earth doped fibre 23 as a
19 function of time 34 during low-power operation. (Note that more exactly, Figure 3
20 shows some form of average inversion 33 as the inversion may vary along the length
21 of the rare-earth doped fibre 23). The higher the inversion 33, the more the stored
22 energy 7, and the higher the gain 8. Four inversions are shown, namely a maximum
23 inversion 30 Nmax, a first cavity inversion 31 Nc, a Q-switched threshold inversion
24 32 Nthr, and an inversion 35. The maximum inversion 30 Nmax corresponds to the
25 maximum inversion that can be achieved by pumping the Q-switched laser 20 with
26 the pump 5 with the switch OFF and with no feedback from reflector 25 and without
27 the presence of the first cavity 27. Figure 3 shows the inversion 33 reaching the
28 maximum inversion 30 by the dotted line 39. The first cavity threshold inversion 31
29 Nc corresponds to the first threshold, namely the threshold of a laser formed by the
30 first cavity 27. The Q-switched threshold inversion 32 Nthr corresponds to the Q-
31 switched threshold, namely the average threshold for the Q-switched laser 20 at a
32 given pulse repetition rate. The inversion 35 corresponds to the inversion N_d within

1   the Q-switched laser at which optical damage occurs within the apparatus, namely

2   the optical damage intensity 72 which is described with reference to Figure 7.

3   Figure 4 shows the optical power 45 Ps of the optical radiation 3 from the Q-

4   switched laser 20. The optical power 45 comprises a plurality of pulses 40 that are

5   triggered by closing the optical switch 24. Figure 5 shows the optical power 50 Pc of

6   the energy limiting signal 29 with time t 34 (in this case the first cavity 27). The

7   output power 50 is zero because the inversion 33 never reaches the first cavity

8   threshold inversion 31 Nc.

9   Figure 6 shows the inversion 33 for the Q-switched laser 20 achieved for

10   either higher power pumping or lower repetition rate. The inversion 33 is clamped

11   periodically at the first cavity threshold inversion 31 Nc. When the optical switch 24

12   is turned on, the Q-switched laser 20 emits the pulses 70 shown in Figure 7, and the

13   inversion 33 falls. The pulses 70 have a peak intensity 71. Figure 8 shows the

14   output 50 of the energy limiting means 2 (in this case the first cavity 27) which

15   comprises pulses 80 which occur when the inversion 33 has reached the first cavity

16   threshold inversion 31 Nc.

17   The presence of the first cavity 27 within the Q-switched laser 20 can be seen

18   to have limited the inversion 33 and hence the peak intensity 71 of the optical

19   radiation 3. This is especially useful for high-power applications for limiting the

20   intensity 71 of the optical radiation 3 such that it is below the optical damage

21   intensity 72 of the apparatus. By optical damage intensity 72, it is meant the

22   intensity of the optical radiation 3 at which optical damage occurs at some location

23   within the apparatus. This aspect of the invention relies upon the first threshold

24   inversion 31 being higher than the Q-switched threshold inversion 32, and the

25   inversion 35 shown with reference to Figures 3 and 6 corresponding to the optical

26   damage intensity 72 being higher than the first threshold 31. By high-power

27   applications it is meant applications in which the intensity of the optical radiation 3

28   within the optical fibre 23 approaches or exceeds the optical damage thresholds of

29   the components within the apparatus. Experimentally, optical damage has been

30   observed in silica optical fibres at intensities above $1GW/cm^2$, and the apparatus is

31   believed to be very useful for intensities above $1GW/cm^2$ and even more so for

32   intensities above $5GW/cm^2$. In typical single mode laser systems, these intensities

33   can correspond to pulse energies greater than 0.1mJ and 0.5mJ respectively, and

34   average output powers greater than around 1W and 5W respectively. For multimode

1   lasers, the pulse energies and optical powers are even higher, the approximate

2   threshold values being calculated from the cross-sectional area of the cores. Other

3   components that can be damaged by high intensity include laser diodes, lenses,

4   fibres such as beam delivery fibres, mirrors, and beam combiners.

5   Figure 9 shows apparatus in the form of a Q-switched laser 90 in which the

6   energy limiting means 2 comprises an energy limiting source 91 and a coupler 92.

7   The energy limiting source 91 provides energy limiting power 94 at an energy limiting

8   wavelength λ_l 285 which acts on the rare-earth doped fibre 23 to reduce the amount

9   of stored energy 7 and gain 8 when the rare-earth doped fibre 23 is pumped by the

10   pump 5.

11   The energy limiting source 91 can be a laser diode, distributed feedback laser

12   diode, a distributed Bragg reflector laser diode, or a fibre laser. The coupler 92 may

13   be an optical coupler, a wavelength division multiplexing coupler, an optical tap

14   (used in reverse), a polarisation beam splitter, or a dichroic mirror. The energy

15   limiting wavelength λ_l 285 must be different from the signal wavelength λ_s 4. The

16   energy limiting power 94 is selected to prevent the inversion 33 of the first amplifier 1

17   from reaching the first threshold 31 Nc (shown with reference to Figure 3). The

18   energy limiting source 91 can be operated continuous wave, modulated, or pulsed.

19   However it is important that the energy limiting source 91 is clamping the Q-switched

20   laser to prevent the inversion 33 reaching the inversion 35 corresponding to the

21   optical damage intensity 72 (shown with reference to Figure 7).

22   Figure 10 shows apparatus in the form of a master oscillator power amplifier

23   100 comprising a seed laser 101, an optional isolator 102, and an optical amplifier

24   103. The seed laser 101 comprises the energy limiting means 2. The seed laser

25   101 can be the Q-switched laser 20 with the optical output 50 being used to clamp

26   the inversion of the optical amplifier 103. The seed laser 101 can also be the Q-

27   switched laser 90 with the energy limiting source 91 configured such that its output

28   94 is configured to co-propagate with the output radiation 3 rather than counter

29   propagate as shown in Figure 9. The isolator 102 can be an optical isolator, an

30   optical circulator, a polariser, an optical switch, an acousto-optical modulator, or an

31   electro-optic modulator such as a Pockels cell or Kerr shutter.

32   Figure 11 shows apparatus in the form of an amplifier 110 configured to

33   amplify an optical signal 113 having an input power P_{in} 115 at the signal

1 wavelength λ_s 4. The energy limiting means 2 comprises a cavity 112. The cavity

2 112 clamps the inversion of the optical fibre 23 in a similar way as described with

3 reference to Figures 2 and 4. The amplifier 110 may be used to replace the amplifier

4 103 in Figure 10.

5 Figure 12 shows apparatus in the form of an amplifier 121 in which the gain

6 medium 6 is provided by the rare-earth doped fibre 23. Two pumps 5 are provided

7 to pump the rare-earth doped fibre 23. The energy limiting means 2 comprises the

8 energy limiting source 91 and the coupler 92. The energy limiting means 2 delivers

9 the energy limiting power 94 at the energy limiting wavelength λ_l 285 to the rare-

10 earth doped fibre 23. The energy limiting power 94 clamps the inversion of the

11 optical fibre 23 in a similar way as described with reference to Figure 9 in order to

12 limit the inversion 33 of the rare-earth doped fibre 23, and in particular the amount of

13 stored energy 7 and gain 8 such that the stored energy 7 is unable to damage the

14 amplifier 121.

15 The amplifiers 110 and 120 are useful for high-power and high-energy

16 applications (>1W continuous wave or >0.1mJ pulses) in which an input signal 113

17 cannot be guaranteed to provide sufficient intensity to prevent stored energy 7 and

18 gain 8 building up in the gain medium 6 to values below those at which the stored

19 energy 7 if released spontaneously will cause damage. In this event, it is essential

20 to provide an energy limiting means 2 to prevent damage to the amplifier 110 or 120.

21 Circumstances in which an input signal 113 might be absent include power-on and

22 power-off modes, power interruption, cable disconnection, and testing

23 subassemblies during manufacture.

24 Figure 13 shows apparatus in the form of a master oscillator power amplifier

25 MOPA 130 comprising a seed laser 131, the optical isolator 102, and a power

26 amplifier 133. The seed laser 131 can be the Q-switched lasers 20 or 90, and the

27 power amplifier 133 can be the amplifiers 110 or 120. Alternatively the seed laser

28 131 can be a semiconductor laser, a distributed feedback laser, a distributed Bragg

29 reflector laser, or a fibre laser. At least one of the seed laser 131 and power amplifier

30 133 contains the energy limiting means 2. The apparatus may include multiple

31 power amplifiers 133 arranged in parallel, configured such that each amplifies the

32 signal 113 from the seed laser 131.

1   Figure 14 shows apparatus in the form of a material processing system 140

2   comprising a plurality of seed lasers 131, a multiplexer 142, a first amplifier 143, a

3   power amplifier 144, a demultiplexer 145, a plurality of scanners 146, a detector 147,

4   and control circuitry 148. The seed lasers 131 can emit at the same wavelength or

5   at different wavelengths. The apparatus is shown with seed lasers 131 emitting at

6   different wavelengths, their output powers being combined by the multiplexer 142

7   which can be a wavelength division multiplexer, and the combined signal being

8   amplified by the first amplifier 143 and the power amplifier 144. At least one of the

9   first and power amplifiers 143, 144 can be the amplifiers 110 or 120. The output

10   from the power amplifier 144 is demultiplexed by the demultiplexer 145 which can be

11   a bulk optic grating separating the different wavelengths to different scanners 146

12   which direct energy 141 to work pieces 1410. Depending upon the configuration of

13   the apparatus, there may be a clamping signal 1411 (eg the energy limiting signal 29

14   of Figure 2) used to limit the output power of a component within the apparatus. This

15   can be filtered out by an optical filter such as the demultiplexer 145 as shown. The

16   apparatus can include the controller 148 to control the signals from the seed lasers

17   131 in synchronism with the scanners 146. This is especially useful in high-

18   throughput laser marking systems in which the same mark is applied to many similar

19   items. Optical feedback can be provided with an optical tap 149 and a detector 147.

20   The optical tap 149 can comprise a beam splitter. Preferably, the optical tap 149

21   provides information about each wavelength in the system. Alternatively or in

22   addition, there can be provided a plurality of optical taps 149 (not shown) located

23   between the demultiplexer 145 and each scanner 146 in order to provide information

24   on each wavelength. The controller 148 may also be used to shape the optical

25   radiation 3 to a desired temporal characteristic 1414 such as a waveform 1412 with

26   substantially rectangular pulses 1413. The detector 147 may be used to feed back

27   the shape of the optical radiation 3 to the controller 148, useful for example for real-

28   time control.

29   Examples of the apparatus have been described with reference to optical fibre

30   amplifiers. These examples can be applied to lasers and amplifiers generally such

31   as diode-pumped solid state lasers, semiconductor lasers, waveguide lasers, and

32   planar-waveguide lasers. The apparatus can include lasers that output in a single

33   spatial mode or in a plurality of spatial modes. The apparatus shown with reference

1   to Figure 14 can be used with a single scanner, and can comprise a single laser of

2   the form shown with reference to Figures 1 to 13.

3   Figure 15 shows a master oscillator power amplifier 150 comprising a

4   ytterbium-doped cladding pumped amplifier 151 and a seed laser 131. The gain

5   medium 6 is the ytterbium-doped fibre 152 which is pumped by between 0W and

6   10W of pump power P_p 153 at a pump wavelength λ_p 154 of 915nm. The pump 5

7   comprises a plurality of single-emitting laser diodes. The energy limiting means 2

8   comprises first and second fibre Bragg gratings 155, 156 reflecting at an energy

9   limiting wavelength λ_l 285 of 1110nm and with a first reflectivity R_1 157 of 5% and a

10   second reflectivity R_2 158 of 5%. The amplifier 151 is driven from a seed laser 131

11   which in this example was a distributed feedback fibre laser emitting an input signal

12   113 with input signal power P_s 1510 of 7mW at a signal wavelength λ_s 4 of 1060nm.

13   When the ytterbium-doped fibre 152 is pumped, the energy limiting means 2

14   emits an energy limiting signal 29. An optional output filter 1515 is shown for

15   removing the energy limiting signal 29 from the optical radiation 3. The output filter

16   1515 can be an optical filter, a grating, a long-period grating, or a fibre Bragg blazed

17   grating.

18   Figure 16 shows the measured gain 161 of the amplifier 151 with increasing

19   pump power P_p 153. The gain 161 is defined as the power ratio of the output

20   radiation 3 at the signal wavelength λ_s 4 to the input signal power P_s 1510. The gain

21   161 increases with pump power 153 and rolls off at a maximum gain 165 of around

22   20dB. Experimentally it has been determined that no self Q-switching occurs in the

23   amplifier 151. In contrast, self Q-switching was evidenced in the amplifier 151 when

24   the first and second fibre Bragg gratings 155, 156 were not provided, the ytterbium-

25   doped fibre 152 failing owing to voids appearing in its core. This is an example of

26   how the energy limiting means 2 comprising the first and second reflectors 281, 282

27   is limiting the gain 161 available for amplifying the input signal 113 when the

28   ytterbium-doped fibre 152 is pumped by the pump 5 such that the stored energy 7 is

29   unable to cause damage to the master oscillator power amplifier 150.

30   The optical radiation 3 emitted by the amplifier 151 of Figure 15 was

31   measured in an optical spectrum analyser without the filter 1515 in place. Figure 17

32   shows the measured optical power spectra 171, 172 versus wavelength 174

33   measured with zero pump power 153 and 2.8W of pump power 153 respectively.

The optical spectrum 171 reveals a signal component 175 at the signal wavelength λ_s 4. The optical spectrum 172 reveals a signal component 176 at the signal wavelength λ_s 4 and a signal component 177 at the energy limiting wavelength λ_l 285. The purpose of the filter 1515 shown in Figure 15 is to filter out the signal component 177 emitted by the amplifier 151.

The amplifier 151 of Figure 15 was modified by exchanging the first and second gratings 155, 156 with gratings having different reflectivities. The gain 161 was measured as a function of pump power 153. Figure 18 shows the gain 181 for 0% reflectivity gratings (ie the gratings were not present), the gain 182 for 3% reflectivity gratings, the gain 183 for 5% reflectivity gratings, and the gain 184 for 15% reflectivity gratings as a function of the pump power 153. The reflectivities referred to here are the first and second reflectivities 157, 158 which in this example are equal. The gain 161 is seen to reduce with increasing reflectivity. Such experimental measurements can be used to determine the reflectivities of the first and second gratings 157, 158 required for a desired gain 161. It will be noted that no measurement results are shown for the case where no gratings were present for pump powers 153 greater than around 3.5W. No catastrophic failures have been seen with the amplifier 151 and similar amplifiers in which the gain 161 has been limited to around 30 to 35dB.

The first and second reflectivities 157, 158 need not be equal. Advantageously, the first reflectivity 157 can be greater than the second reflectivity 158. Such an arrangement will tend to emit the energy limiting signal 29 away from the seed source 131 and may remove the need for an isolator separating the seed source 131 from the amplifier 151. Alternatively, it may be advantageous to make the second reflectivity 158 greater than the first reflectivity 157. This will reduce the amount of energy limiting signal 29 emitted in the same direction as the optical radiation 3, and if the second reflectivity is greater than 90%, and preferably greater than 99%, may remove the need for the optical filter 1515.

From Figure 18, it is believed that the reflectivity for at least one of the first and second reflectors 155, 156 should be at least 0.01% (corresponding to at least 0.01% of optical radiation being reflected at the energy limiting wavelength 285).

Figure 19 shows a graph of the amplified spontaneous emission 191 measured as a function of wavelength 174 for the amplifier 151 without the first and

1	second gratings 155, 156 and output filter 1515 in place. The amplified spontaneous
2	emission 191 is shown for various levels of pump power 153 between 0.642W and
3	3.4W, the higher the pump power 153, the greater the amplified spontaneous
4	emission 191.
5	Figure 20 shows the data of Figure 19 replotted as the double-pass (or round
6	trip) small signal gain 201 of the gain medium 6 (ie not including the reflectivities).
7	These data were generated by doubling the values in dB indicated at each
8	wavelength 174 in Figure 19 and then adding a constant gain in order to normalize
9	the values to a measured gain at a fixed wavelength. Also shown is the product 209
10	of the first and second reflectivities R_1, R_2 158, 159 required to achieve a round-trip
11	gain (not shown) through the amplifier 151 of unity. Unity round-trip gain 208 (not
12	shown) corresponds to the onset of lasing. For example, a double pass gain 201 of
13	60dB corresponds to an (intensity) gain of 10^6. The product R1.R2 209 therefore
14	needs to be 10^{-6} in order to achieve a round-trip gain 208 of unity.
15	Three example desired gains 202, 203, 204 are shown at a signal wavelength
16	of 1060nm and are indicated in Figure 20 by the square 202, triangle 203 and circle
17	204 respectively. If an energy limiting wavelength λ_l 285 of 1110nm is selected, the
18	required grating reflectivity products R1.R2 209 can be found by extrapolating along
19	the gain curves 201 to arrive the energy limiting wavelength λ_l 285 of 1110nm and
20	reading off the grating reflectivity product R1.R2 209. In this example, these are
21	indicated by the square 205, triangle 206 and circle 207. As can be seen, the
22	required grating reflectivity products R1.R2 209 is equal to the reciprocal of twice the
23	small signal gain 8 at the energy limiting wavelength 285.
24	The square 202 corresponds to a desired gain 161 of 10dB at the signal
25	wavelength λ_s 4 (half the double pass gain 201 of 20dB). The corresponding small
26	signal gain 161 at the energy limiting wavelength λ_l 285 is found by extrapolating
27	along the gain curves 201 to the square 205. Figure 20 shows that in order to
28	achieve the desired gain 161 of 10dB at the signal wavelength 4, the grating
29	reflectivity products R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm
30	indicated by the square 205 needs to be 2.5×10^{-2}. The grating reflectivity product
31	R1.R2 209 is equal to the reciprocal of twice the small signal gain 161 at the energy
32	limiting wavelength λ_l 285. This product can be achieved by first and second
33	reflectivities 157, 158 both equal to 16%. Referring to Figure 18, the gain 184

1   indicated by the squares was achieved with first and second grating reflectivities

2   157, 158 of 15% and resulted in the gain 161 being clamped at around 10dB.

3   Referring to Figure 20, the triangle 203 corresponds to a desired gain 161 of

4   19dB at the signal wavelength λ_s 4 (half the double pass gain 201 of 38dB). The

5   corresponding small signal gain 161 at the energy limiting wavelength λ_l 285 is found

6   by extrapolating along the gain curves 201 to the triangle 206. The grating reflectivity

7   product R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm indicated by

8   the triangle 206 needs to be 2.5 x 10^{-3} which is equal to the reciprocal of twice the

9   small signal gain 161 at the energy limiting wavelength λ_l 285. The product 209 can

10   be achieved by first and second reflectivities 157, 158 both equal to 5%. Referring to

11   Figure 18, the gain 183 indicated by the triangles was achieved with first and second

12   grating reflectivities 157, 158 of 5% and resulted in the gain 161 of the amplifier 151

13   being clamped at around 20dB at the signal wavelength λ_s 4.

14   Referring to Figure 20, the circle 204 corresponds to a desired gain 161 of

15   22dB at the signal wavelength λ_s 4 (half the double pass gain 201 of 44dB). The

16   corresponding small signal gain 161 at the energy limiting wavelength λ_l 285 is found

17   by extrapolating along the gain curves 201 to the circle 207. The grating reflectivity

18   products R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm indicated by

19   the circle 207 needs to be 8 x 10^{-4} which is equal to the reciprocal of twice the small

20   signal gain 161 at the energy limiting wavelength λ_l 285. The product 209 can be

21   achieved by first and second reflectivities 157, 158 both equal to 2.8%. Referring to

22   Figure 18, the gain 182 indicated by the circles was achieved with first and second

23   grating reflectivities 157, 158 of 3% and resulted in the gain 161 of the amplifier 151

24   being clamped at around 25dB.

25   With reference to Figure 20, it is seen that if the gain medium 6 when pumped

26   by the pump radiation 15 has a desired gain 161 at the signal wavelength λ_s 4, and a

27   corresponding small signal gain 161 at the energy limiting wavelength λ_l 285, then

28   the product 209 of the first and second reflectivities 157, 158 should be substantially

29   equal to the reciprocal of twice the small signal gain 161 at the energy limiting

30   wavelength λ_l 285.

31   The desired gain 161 at the signal wavelength λ_s 4 should be chosen to

32   minimize the likelihood of damage to the amplifier 151. This is achieved by limiting

33   the corresponding small signal gain 161 at the wavelength at which the small signal

1   gain 161 peaks. With reference to Figure 20, the corresponding small signal gain

2   161 to the circle 204 is shown by the cross 208, which corresponds to twice the

3   maximum gain 14 of at the maximum gain wavelength 18 of 1076nm (the factor of 2

4   occurs because Figure 20 shows the double pass small signal gain 201).

5   If the gain medium is pumped by at least 1W of the pump radiation 15, then it

6   is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less

7   than 40dB. This is to prevent optical damage from occurring. In this example, the

8   product 209 of the first and second reflectivities 157, 158 would be approximately

9   10^{-4} at 1110nm.

10   If the gain medium is pumped by at least 10W of the pump radiation 15, then

11   it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less

12   than 30dB. In this example, the product 209 of the first and second reflectivities 157,

13   158 would be approximately 5×10^{-4} at 1110nm.

14   If the gain medium is pumped by at least 100W of the pump radiation 15, then

15   it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less

16   than 25dB. In this example, the product 209 of the first and second reflectivities 157,

17   158 would be approximately 10^{-3} at 1110nm.

18   If the gain medium is pumped by at least 1000W of the pump radiation, then it

19   is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less

20   than 20dB. In this example, the product 209 of the first and second reflectivities 157,

21   158 would be approximately 5×10^{-3} at 1110nm.

22   The above are general guidelines that have been found useful for cladding

23   pumped amplifiers. However, the strength of the first and second reflectivities 157,

24   158 required in any particular embodiment is dependent upon the amount of pump

25   radiation 15 delivered to the gain medium 6 and also upon the spectroscopy of the

26   gain medium 6. It is therefore sensible to optimise the first and second reflectivities

27   157, 158 experimentally.

28   Figures 21 to 26 show modelling results for the amplifier 121 shown with

29   reference to Figure 12, in which the energy limiting means 2 is provided by the

30   energy limiting power 94 supplied by the energy limiting source 91. The modelling

31   results are for a rare-earth doped fibre 23 doped with ytterbium. Figure 21 shows

32   the small signal gain 211 for zero energy limiting power 94, and the small signal gain

33   212 for 8.4mW of energy limiting power 94 at an energy limiting wavelength λ_l 285

1   of 1110nm. The pump power P_p 153 delivered to the rare-earth doped fibre 23 by

2   the pumps 5 was 4W (in total), and was at a pump wavelength λ_p 154 of 915nm.

3   The small signal gains 211 and 212 are plotted as a function of the signal input

4   power 115 at a signal wavelength λ_s 4 of 1060nm. The gain 211 is seen to increase

5   with reducing signal input power 115. Eventually the gain 211 will be limited by the

6   amount of pump power P_p 153 and by amplified spontaneous emission that is

7   emitted by the rare-earth doped fibre 23.

8   Figure 22 shows the small signal gain 221 as a function of wavelength 174 for

9   the amplifier 121 that has been clamped with 8.5mW of energy limiting power 94.

10   The small signal gain 222 at the energy limiting wavelength λ_l 285 of 1110nm is

11   approximately 3dB less than the small signal gain 212 at the signal wavelength λ_s 4.

12   The small signal gain 212 is approximately 8dB less than the maximum gain 14. A

13   differential gain 223 equal to the maximum gain 14 (at the maximum gain

14   wavelength 18) minus the small signal gain 212 can be defined as shown in

15   Figure 22. The differential gain 223 is 8dB, that is, the amplifier 121 can provide an

16   additional 8dB gain over and above the gain 211 and 212 shown in Figure 21.

17   Referring to Figure 21, the gain 211 of 40dB at the signal wavelength λ_s 4

18   corresponds to maximum gain 14 at the maximum gain wavelength 18 of 48dB, and

19   as can be seen, the gain 211 is rising with reducing signal input power 115. A

20   maximum gain 14 of 48dB is capable of generating an unwanted pulse that could

21   damage optical components within the amplifier 121. Such pulses have been

22   experienced with pump diodes breaking, and also catastrophic failure of optical

23   fibres, even at relatively low pump powers of 1W. The energy limiting power 94 of

24   8.5mW clamps the gain 212 at approximately 25dB for low signal input powers 115.

25   The gain 212 of 25dB at the signal wavelength λ_s 4 together with the differential gain

26   223 of 8dB corresponds to a maximum gain 14 of 33dB at the maximum gain

27   wavelength 18. The energy limiting power 94 reduces the amount of stored energy 7

28   that can be stored by the rare-earth doped fibre 23, and thus ensures that the gain

29   medium 6 is unable to release the stored energy 7 at a level that would damage the

30   amplifier 121.

31   Figure 23 shows the small signal gain 231 for zero energy limiting power 94,

32   and the small signal gain 232 for 200mW of energy limiting power 94 at an energy

33   limiting wavelength λ_l 285 of 1082nm. The pump power P_p 153 delivered to the rare-

1   earth doped fibre 23 by the pumps 5 was 40W (in total), and was at a pump

2   wavelength λ_p 154 of 915nm. The small signal gains 231 and 232 are plotted as a

3   function of the signal input power 115 at a signal wavelength λ_s 4 of 1094nm. The

4   gain 231 is seen to increase with reducing signal input power 115, which makes the

5   amplifier 121 susceptible to damage by release of the stored energy 7. The gain 232

6   is clamped to 23dB at low signal input powers 115.

7   Figure 24 shows the corresponding small signal gain 241 as a function of

8   wavelength 174 for the amplifier 121 that has been clamped with 200mW of energy

9   limiting power 94. The signal wavelength λ_s 4 corresponds to the maximum gain

10   wavelength 18 since the gain 241 is a maximum at the signal wavelength λ_s 4. The

11   differential gain 223, defined with reference to Figure 22, is therefore zero. Referring

12   to Figure 23, the energy limiting power 94 reduces the amount of stored energy 7

13   that can be stored by the rare-earth doped fibre 23, and thus ensures that the gain

14   medium 6 is unable to release the stored energy 7 at a level that would damage the

15   amplifier 121.

16   Figure 25 shows the small signal gain 251 for zero energy limiting power 94,

17   and the small signal gain 252 for 7W of energy limiting power 94 at an energy

18   limiting wavelength λ_l 285 of 1104nm. The pump power P_p 153 delivered to the rare-

19   earth doped fibre 23 by the pumps 5 was 400W (in total), and was at a pump

20   wavelength λ_p 154 of 915nm. The small signal gains 251 and 252 are plotted as a

21   function of the signal input power 115 at a signal wavelength λ_s 4 of 1094nm. The

22   gain 251 is seen to increase with reducing signal input power 115, which makes the

23   amplifier 121 susceptible to damage by release of the stored energy 7. The gain 232

24   is clamped to 16dB at low signal input powers 115.

25   Figure 26 shows the corresponding small signal gain 261 as a function of

26   wavelength 174 for the amplifier 121 that has been clamped with 7W of energy

27   limiting power 94. The signal wavelength λ_s 4 is 3nm less than the maximum gain

28   wavelength 18. The gain 252 is approximately the same as the maximum gain 14.

29   The differential gain 223, defined with reference to Figure 22, is approximately zero.

30   Note that the differential gain 223 is approximately zero provided that the signal

31   wavelength λ_s 4 is within 10nm of the maximum gain wavelength 18. Referring to

32   Figure 25, the energy limiting power 94 reduces the amount of stored energy 7 that

33   can be stored by the rare-earth doped fibre 23, and thus ensures that the gain

1   medium 6 is unable to release the stored energy 7 at a level that would damage the

2   amplifier 121.

3   Referring to Figure 1, 9 and 12, it is preferable for a gain medium 6 that is

4   pumped with at least 1W of pump power P_p 153 (where problems are first

5   encountered with ytterbium-doped fibre lasers), that the energy limiting source 91

6   should provide at an energy limiting wavelength 285 an energy limiting power 94

7   greater than -40dB relative to the pump power 153. The energy limiting power 94

8   acts on the gain medium 6 to reduce the amount of stored energy 7 and gain 8 when

9   the gain medium 6 is pumped by the pump 5 such that the stored energy 7 is unable

10   to cause damage to the apparatus 10. The energy limiting power 94 has been

11   referenced to the pump power 153 and values selected assuming that the energy

12   limiting wavelength 285 is close to the maximum gain wavelength 18.

13   If the gain medium 6 is pumped by at least 10W of the pump power P_p 153,

14   then it is preferable that the energy limiting source 91 provides an energy limiting

15   power 94 greater than -30dB relative to the pump power P_p 153.

16   If the gain medium is pumped by at least 100W of the pump power P_p 153,

17   then it is preferable that the energy limiting source 91 provides an energy limiting

18   power 94 greater than -25dB relative to the pump power P_p 153.

19   If the gain medium is pumped by at least 1000W of the pump power P_p 153,

20   then it is preferable that the energy limiting source 91 provides an energy limiting

21   power 94 greater than -20dB relative to the pump power P_p 153.

22   In the above four examples (corresponding to pump powers P_p 153 of greater

23   than 1W, 10W, 100W, and 1000W), the energy limiting power 94 should be

24   increased as the energy limiting wavelength 285 moves away from the maximum

25   gain wavelength 18 by a factor corresponding to the difference in the maximum gain

26   14 and gain 8 of the gain medium 6 at the energy limiting wavelength 285.

27   Experimental optimisation of these energy limiting power 94 and energy

28   limiting wavelength 285 is advisable. If optical damage (particularly of pumps, fibres

29   and other optical devices) is experienced, then the energy limiting power 94 should

30   be increased.

31   With reference to the embodiments described in Figures 1 to 26, the energy

32   limiting wavelength 285 can be in the same emission band 9 as the signal

33   wavelength 4.

1   Alternatively, the energy limiting wavelength 285 can be in a different

2 emission band 9 from the signal wavelength 4. For example with erbium-ytterbium

3 dopants, the gain medium 6 can be clamped in the lower emission band (from

4 around 970nm to 1150nm, but preferably between 1070nm to 1150nm) and the

5 signal wavelength 4 can be in higher emission band (from around 1530nm to

6 1600nm). Clamping in the lower emission band is advantageous because the

7 ytterbium dopant has faster dynamics.

8   Alternatively, the gain medium 6 can be clamped in the higher emission band

9 (from around 1530 to 1600nm) and the signal wavelength 4 can be in the lower

10 emission band (from around 970nm to 1150nm, but preferably between 1070nm to

11 1150nm). The latter alternative is attractive because it offers the benefits of

12 increased reliability that accrue from the energy limiting means 2, yet when the input

13 signal is present, the effect of the energy limiting means 2 on the signal will be less

14 significant as the energy limiting means 2 is operating on a different dopant (the

15 erbium). Advantages include better efficiency and transient behaviour.

16   Advantages of having the energy limiting wavelength 285 greater than the

17 signal wavelength 4 include less reabsorption at the energy limiting wavelength 285.

18 This implies that lower energy limiting powers 94 or first and second reflectivities

19 157, 158 can be used to clamp the gain medium 6. In addition, the transient

20 behaviour of amplifiers and lasers may be better (for example the Q-switched laser

21 of Figure 2).

22   The energy limiting wavelength 285 can be less than the signal wavelength 4.

23 This may have advantages if more than one energy signal wavelength 285 were

24 used, for example one greater and one less than the signal wavelength 4.

25   Preferably, the energy limiting wavelength 285 and the maximum gain

26 wavelength 18 are separated by less than 10nm in order that less energy limiting

27 power 94 can be used. Alternatively, it can be advantageous to have the energy

28 limiting wavelength 285 and the maximum gain wavelength 18 separated by more

29 than 10nm in order to facilitate filtering out optical radiation at the energy limiting

30 wavelength 285 using optical filters 1515.

31   Although much of the discussion pertaining to Figures 2, 9, 11, 12 and 15

32 have centred on ytterbium, the rare-earth doped fibre 23 may be core pumped, or

33 may be a cladding pumped optical fibre comprising a core, an inner cladding for

34 guiding pump radiation supplied by the pump, and an outer cladding, and in which

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1　the rare earth dopant is disposed in at least one of the core and the inner cladding.

2　The rare-earth dopant may be selected from the group comprising ytterbium, erbium,

3　neodymium, praseodymium, thulium, samarium, holmium and dysprosium, erbium

4　codoped with ytterbium, or neodymium codoped with ytterbium. The invention also

5　extends to alternative gain media 6, for example crystals in rod and disk form.

6　　It is to be appreciated that the embodiments of the invention described above

7　with reference to the accompanying drawings have been given by way of example

8　only and that modifications and additional components may be provided to enhance

9　performance. In addition, the invention can be considered to be an amplifier, a laser,

10　a master oscillator power amplifier, a Q-switched laser, a source of amplified

11　spontaneous emission, or a continuous wave laser. The invention can also

12　considered to be a laser for material processing.

13　　The present invention extends to the above-mentioned features taken in

14　isolation or in any combination.